

Sneutrino Dark Matter in Light of PAMELA

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In the $U(1)_{B-L}$ extension of the minimal supersymmetric standard model the right-handed sneutrino is a natural candidate for thermal dark matter. Sneutrino annihilation at the present time can be considerably enhanced due to the exchange of the lightest field in the Higgs sector that breaks $U(1)_{B-L}$. The annihilation mainly produces taus (or muons) by the virtue of $B - L$ charge assignments. A sneutrino mass of $1 - 2$ TeV provides a good fit to the PAMELA and is compatible with the latest results from the FERMI experiment. In addition, the sneutrino-nucleon elastic scattering cross section is within the reach of the upcoming and future direct detection experiments.

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I. INTRODUCTION

There are currently major experimental efforts for direct and indirect detection of the dark matter particle. The indirect detection investigates astrophysical effects of dark matter annihilation in the galaxy, including signatures in the cosmic rays. The recently published results by PAMELA experiment show an excess of positron flux at energies above 10 GeV [1], while no excess of anti-proton flux is observed [2]. Another cosmic ray experiment called ATIC (a balloon experiment) has also recently published data where one observes an excess in the $e^+ + e^-$ spectrum with a peak around 600 GeV [3]. However, the latest results from the FERMI [4] and H.E.S.S. [5] experiments do not confirm the peak at the high energies reported by ATIC.

While there could be astrophysical explanations for these anomalies (e.g. from nearby pulsars [6]), it is reasonable to ask whether they can be attributed to the effect of dark matter annihilation in the galaxy. Barring a large astrophysical boost factor $10^3 - 10^4$, which might be difficult to obtain based on recent analysis of halo substructure [7], a dark matter explanation requires an annihilation cross section much larger than the canonical value $\sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$ [8] and dominantly leptonic final states [9]. This cannot be achieved for the neutralino dark matter in the minimal Supergravity (mSUGRA) model. There have been proposals for new dark matter models [9, 10] in which the dark matter candidate belongs to a hidden sector, and an acceptable thermal relic density is obtained via new gauge interactions. The key ideas of these models are that the dark matter annihilation today is enhanced by a Sommerfeld effect [11] due to the existence of light bosons and that annihilation mainly produces lepton final states via symmetry of the hidden sector.

Here we consider an explicit model where dark matter belongs to the visible sector and can explain the positron excess. It is based on a simple extension of the minimal supersymmetric standard model (MSSM) that includes a gauged $U(1)_{B-L}$, with the right-handed (RH) sneutrino being the dark matter [12].

II. THE MODEL

The $B - L$ extension of the MSSM [13] is well motivated since it automatically implies the existence of three RH neutrinos through which one can explain the neutrino masses and mixings. The minimal model contains a new gauge boson Z' , two new Higgs fields H'_1 and H'_2 , the RH

neutrinos N , and their supersymmetric partners. The superpotential is (the boldface characters denote superfields)

$$W = W_{\text{MSSM}} + W_{B-L} + y_D \mathbf{N}^c \mathbf{H}_u \mathbf{L}, \quad (1)$$

where \mathbf{H}_u and \mathbf{L} are the superfields containing the Higgs field that gives mass to up-type quarks and the left-handed (LH) leptons respectively. For simplicity, we have omitted the family indices. The W_{B-L} term contains \mathbf{H}'_1 , \mathbf{H}'_2 , \mathbf{N}^c and its detailed form depends on the charge assignments of the new Higgs fields. The last term on the RH side of Eq. (1) is the neutrino Yukawa coupling term.

The $U(1)_{B-L}$ is broken by the vacuum expectation value (VEV) of H'_1 and H'_2 , which we denote by v'_1 and v'_2 respectively. This results in a mass $m_{Z'} = g_{B-L} Q_1 \sqrt{v'^2_1 + v'^2_2}$ for the Z' gauge boson. Here g_{B-L} is the gauge coupling of $U(1)_{B-L}$, and $+Q_1$, $-Q_1$ are the $B-L$ charges of H'_1 , H'_2 respectively. We have three physical Higgs fields ϕ , Φ (scalars) and \mathcal{A} (a pseudo scalar). The scalar Higgses are related to the real parts of H'_1 , H'_2 through the mixing angle α' :

$$\begin{aligned} H'_1 &= \frac{v'_1 + \cos \alpha' \Phi - \sin \alpha' \phi}{\sqrt{2}} + \frac{H'_{1,I}}{\sqrt{2}} \\ H'_2 &= \frac{v'_2 + \sin \alpha' \Phi + \cos \alpha' \phi}{\sqrt{2}} + \frac{H'_{2,I}}{\sqrt{2}}, \end{aligned} \quad (2)$$

where $H'_{1,I}, H'_{2,I}$ represent the imaginary parts. The masses of the Higgs fields follow $m_\phi^2 < \cos^2(2\beta') m_{Z'}^2$, and $m_\Phi, m_{\mathcal{A}} \sim m_{Z'}$ ($\tan \beta' \equiv v'_2/v'_1$).

A natural dark matter candidate in this model is the sneutrino \tilde{N} ¹. The main processes for annihilation of dark matter quanta are then governed by the D -term contribution to the scalar potential [12], with the dominant mode being $\tilde{N}^* \tilde{N} \rightarrow \phi\phi$. The ϕ subsequently decays into fermion-antifermion pairs via a one-loop diagram containing two Z' bosons. The decay rate is given by:

$$\Gamma(\phi \rightarrow f\bar{f}) = \frac{C_f}{2^7 \pi^5} \frac{g_{B-L}^6 Q_f^4 Q_\phi^2 m_\phi^5 m_f^2}{m_{Z'}^6} \left(1 - \frac{4m_f^2}{m_\phi^2}\right)^{3/2}, \quad (3)$$

where Q_f and Q_ϕ are the $B-L$ charges of the final state fermion and the ϕ respectively, m_f is the fermion mass, and C_f denotes color factor. Since the $B-L$ charge of leptons is three times larger than that of quarks, the leptonic branching ratio is naturally larger than that for quarks. For $\tan \beta' \approx 1$, we can have $m_\phi \ll m_{Z'}$. If $m_\phi > 2m_b$, the dominant decay mode is $\phi \rightarrow \tau^- \tau^+$ final state, while the branching ratio for the $\phi \rightarrow b\bar{b}$ mode is ≈ 7 times smaller.

The annihilation cross section at the present time has Sommerfeld enhancement as a result of the attractive force between sneutrinos due to the ϕ exchange that leads to an attractive potential $V(r) = -\alpha(e^{-m_\phi r}/r)$ in the non-relativistic limit [11], where

$$\alpha = \frac{g_{B-L} m_{Z'} \sin(\alpha' + \beta')}{4m_{\tilde{N}}}, \quad (4)$$

and $m_{\tilde{N}}$ is the sneutrino mass.

¹ Another candidate is the lightest neutralino in the new sector [14].

III. SNEUTRINO DARK MATTER AND PAMELA

As an explicit example, we choose the $B - L$ charge for H'_1 (i.e. Q_1) to be $3/2$. The $B - L$ charges of quarks and leptons are chosen to be $1/6$ and $-1/2$ respectively.

We use reasonable values for the model parameters, i.e., $\tan\beta' \approx 1$, $m_{Z'} > 1.5$ TeV, $\mu' = 0.5 - 1.5$ TeV (μ' being the Higgs mixing parameter in the $B - L$ sector), soft masses for the Higgs fields $m_{H'_{1,2}} = 200 - 600$ GeV, and soft gaugino mass $M_{\tilde{Z}'} \geq 1$ TeV. The Z' mass used in the calculation obeys the LEP and Tevatron bounds [15] for our charge assignments. The sneutrino mass is chosen to be between 800 GeV and 2 TeV in order to explain the PAMELA data.

We use **DarkSUSY-5.0.2** [16] to calculate the positron flux from dark matter annihilation. Each pair annihilation in our model produces 2 ϕ 's that yield four fermions upon their decay. For this reason, we generally need a heavier sneutrino compared to models in which the pair annihilation directly produces fermions. We normalize the positron fraction by a factor $k_b = 1.11$ according to [17]. Here we assume NFW profile [18] for the dark matter halo and MED parameters for the propagation as defined in [19].

In Figure 1, we show our fit to the PAMELA data for $m_{\tilde{N}} = 1.5$ TeV for $\tau^+\tau^-$ and $\mu^+\mu^-$ final state cases. We found that with an enhancement factor of 10^3 the chi-square values (including only points with energy greater than 10 GeV) for a sneutrino mass of 1.5 TeV are small, i.e. 2.9 and 5.5 for $\tau^+\tau^-$ and $\mu^+\mu^-$ respectively. We can raise m_ϕ up to ~ 15 GeV and still have acceptable anti-proton flux. Also, we find that for $\tau^+\tau^-$ final state the $e^+ + e^-$ spectrum at higher energies is compatible with the recent results from FERMI satellite.

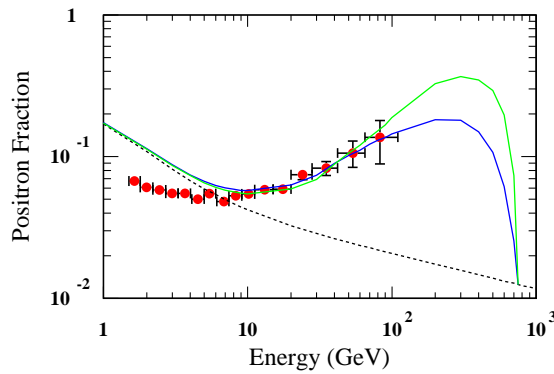


FIG. 1: We show a fit to the PAMELA data when the ϕ decays mostly to taus (dark blue) or muons (light green) for a sneutrino mass of 1.5 TeV and an enhancement factor of 10^3 . The dashed line is the expected background cosmic rays.

IV. DIRECT DETECTION

In our model the elastic scattering of the sneutrino occurs via the Z' exchange with the nucleus in the t -channel. This leads to only a spin-independent contribution since the $B - L$ charges of the left and right quarks are the same. In Figure 2, we show the \tilde{N} - p scattering cross section for the model points that satisfy the relic density constraint $0.096 < \Omega_{DM} h^2 < 0.124$ [20]. We see that the cross section can be in the $10^{-11} - 10^{-9}$ pb range, which is close to the reach of the upcoming dark matter direct detection experiments [21]. This also gives rise to neutrino signals from dark matter annihilation that are detectable at the IceCube neutrino telescope [22].

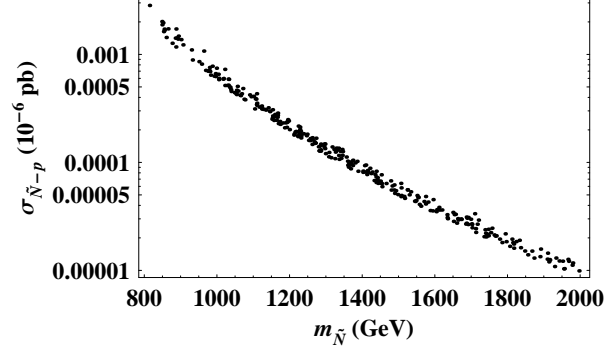


FIG. 2: We show the direct detection cross section as a function of sneutrino mass.

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